RESEARCH DEPARTMENT

Aspects of frequency-division-multiplex colour systems for television field-store standards converters

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THE BRITISH BROADCASTING CORPORATION
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RESEARCH DEPARTMENT

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SUMMARY

This report describes an investigation into certain aspects of a proposal to use a frequency-division-multiplex system for the transmission of a colour television signal through the 'advanced' Field-Store Standards Converter. The investigation showed that the use of such a system, within the bandwidth of currently-available ultrasonic delays, would be impracticable because of interference from intermodulation products generated by non-linearity in radio-frequency amplifiers and switches. It was established that an r.f. bandwidth of about 11·5 MHz would be necessary if reasonable picture quality is to be achieved.

1. INTRODUCTION

The ultrasonic delays used in field-store standards converters require a radio-frequency carrier for the video-signal. Since transcoding is invariably part of the conversion process, the colour coding system can be chosen to suit the needs of the converter and whilst signals of the NTSC type have the advantage of needing only one r.f. carrier, this form of signal presents some problems.

One of the difficulties in using a composite colour signal of the NTSC type in 'advanced' Field-Store Standards Converters[1,2] is that the phase of the colour sub-carrier on the converted output signal is not coherent from line to line because of arbitrary delay errors. Decoding of the composite signal is thus complicated by the need for a line-by-line phase-shifter. To avoid this and other difficulties, an alternative form of colour system has been proposed.[2] In the proposed system the input video signal is first split into luminance and two colour-difference signals, R-Y and B-Y, and three separate radio-frequency (r.f.) carriers, each modulated by one of these signals, are then passed simultaneously through the converter. Asymmetric-sideband transmission is used for each signal, to conserve bandwidth, and each carrier is frequency modulated to minimize the effects of the inevitable gain variations which occur in the conversion process.

A possible difficulty with this frequency-division-multiplex (f.d.m.) proposal, however, is that non-linearity in the r.f. amplifiers, electronic switches and other devices in the converter, would result in the generation of intermodulation products (i.p.s) which could cause mutual interference between the three signals. This difficulty is aggravated by the fact that, although the degree of non-linearity in each individual amplifier or switch may be small, the total level of intermodulation products could be quite high at the end of the long chain of amplifiers and switches used in the 'advanced' Field-Store Standards Converter.

This report is concerned with a theoretical and experimental investigation of these aspects of the proposal.

2. THEORETICAL ASSESSMENT OF THE INTERMODULATION PROBLEM

2.1. The General Intermodulation Process

The instantaneous voltage v_o at the output of an active network having a non-linear amplitude transfer characteristic may be represented by the equation

$$v_o = \alpha\, v_i + \beta\, v_i^2 + \gamma\, v_i^3 + \ldots\ldots\ldots \quad (1)$$

where α, β, γ are constants and v_i is the instantaneous input voltage to the network. When v_i comprises two or more fundamental frequencies the output of the network will contain components at the harmonics and at sum- and difference-combination frequencies, as well as the wanted fundamental frequencies.

The coefficients of some 'typical products'* which arise from the 2nd and 3rd order terms in equation (1) when the input voltage consists of three frequencies

$$v_i = a_1 \cos 2\pi f_1 t + a_2 \cos 2\pi f_2 t + a_3 \cos 2\pi f_3 t$$

are shown in Table 1. The information given in this Table was derived from a table of intermodulation products calculated by Wass.[3]

TABLE 1

Frequency	Amplitude proportional to	Product arising from
$2f_1$	$1/2\ \beta a_1^2$	2nd order term βv_1^2
$\pm f_1 \pm f_2$	$\beta a_1 a_2$	
$\pm 2f_1 \pm f_2$	$3/4\ \gamma a_1^2 a_2$	3rd order term γv_1^3
$\pm f_1 \pm f_2 \pm f_3$	$3/2\ \gamma\ a_1 a_2 a_3$	

It will be shown in Sections 2.2 and 2.4 that the 'typical products' given in Table 1 are all of particular interest in the 3-carrier f.d.m. proposal. Products having the same frequency could also be generated by higher-order terms in equation (1) but these are unlikely to be significant in practice unless severe over-loading of r.f. amplifiers (i.e. active networks) occurs.

* A 'typical product' represents a particular class of the products of non-linearity which may have equal amplitudes but differ in having different component frequencies and a different arrangement of positive and negative signs connecting the frequencies. It is of interest to note that the sum of the coefficients of the component frequencies of an i.p. gives the lowest order of non-linear term from which the i.p. can arise.

2.2. Intermodulation Products in the Proposed F.D.M. System

Fig. 1 shows the approximate spectral arrangement of signals proposed for the f.d.m. system, together with the frequencies of possible i.p.s (corresponding to the undeviated f.m. carriers) which fall either within, or close to, the pass-bands of the wanted signals. Because of the general difficulty of achieving a wide bandwidth in ultrasonic delay lines, this arrangement of signals is attractive as it occupies the minimum bandwidth consistent with acceptable resolution of the converted picture. It was also proposed that in order to maintain the required luminance signal-to-noise ratio, the amplitude of each chrominance carrier should be one half that of the luminance carrier. The peak-to-peak amplitude of the combined signals would, of course, be equal to the normal peak-to-peak working level.

Of the four possible i.p.s shown in Fig. 1 the two most important are those which lie within the luminance signal pass-band; that is $f_1 - f_2 + f_3$ and $2f_2 - f_3$, which are spaced 1 MHz and 3 MHz respectively from the luminance carrier. Both of these interfering signals are generated directly by the fundamental frequencies subjected to 3rd order non-linearity, but it is of interest to note that they could also be produced by 2nd order non-linearity in a chain of cascaded non-linear networks unless band-pass filters were inserted between each network. Taking into account the relative amplitudes of the three fundamental frequencies and referring to equation (1) and Table 1, the amplitudes of these

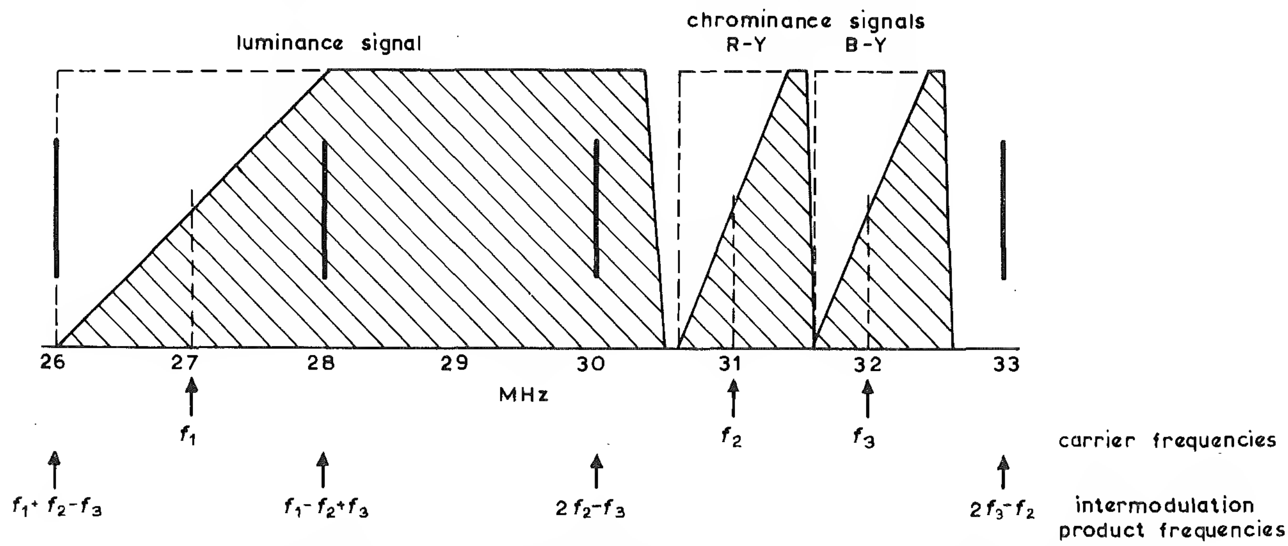

Fig. 1 - Approximate spectral components of proposed f.d.m. system and possible interfering intermodulation products

two 3rd order i.p.s relative to that of the luminance carrier would be as shown in Table 2.

TABLE 2

Frequency	Amplitude relative to luminance carrier
$2f_2 - f_3$	$3/32\ (\gamma/\alpha a_1)$
$f_1 - f_2 + f_3$	$12/32\ (\gamma/\alpha a_1)$

The predicted level of the three-frequency term is therefore 12 dB higher than that of the two-frequency term assuming only 3rd order non-linearity.

2.3. Theoretical Estimate of the Permissible Level of Intermodulation Products from each Unit

The protection ratio required by a frequency-modulated, monochrome television signal for 'just not perceptible'* interference from a single unwanted c.w. signal has been determined,[4] and for an unwanted signal spaced 1 MHz or more from the wanted carrier this ratio is about 45 dB, when normal pre- and de-emphasis is used.

The interfering signals in the proposed f.d.m. system would be frequency-modulated by chrominance information in the case of the $2f_2 - f_3$ term and by a mixture of luminance and chrominance information in the case of the $f_1 - f_2 + f_3$ term. The monochrome c.w. protection ratio may reasonably be taken, however, as a guide to that required for the luminance signal against the modulated unwanted signals in the f.d.m. system.

When a number of similar non-linear networks are connected in cascade, the i.p.s generated in each unit would tend to add directly, provided that the i.p.s and fundamental frequencies are not subject to significant group delay distortion. This is because an i.p. generated in one non-linear source tends to be co-phased with the same i.p. contributed from a previous non-linear source. It follows, therefore, that if a number of identical non-linear sources are cascaded, and if each source has unity gain, (as is the case with the delay units and r.f. switches of the 'advanced' Field-Store Standards Converter) the final level of a 3rd order i.p. would be expected to be N times the level generated in one unit, where N is the total number of units.

So far, only the effects of 3rd order non-linearity have been considered. If band-pass filters are not inserted between each unit in the transmission path, the 3rd order type of i.p. (e.g. $2f_2 - f_3$) may also be generated by 2nd order non-linearity. Thus, $2f_2$ emerging from the first unit combines with f_3 in the second unit to produce $2f_2 - f_3$, and this process repeats along the chain of units. Similarly, $f_1 + f_3$ emerging from one unit combines with f_2 in the next unit to produce $f_1 - f_2 + f_3$.* It may be shown that the final level of the 2nd order contribution to the 3rd order type of i.p. at the end of a chain of N identical, unity gain, non-linear units is $N(N-1)/2$ times the level generated in one pair of units, assuming in-phase addition of the relevant components along the chain of units. At the beginning of the chain of units the i.p.s produced in this way would tend to be of lower level than the corresponding 3rd order terms because the 2nd order mode of generation involves two successive stages of 2nd order non-linearity. At the end of the chain of units, however, the 2nd order contribution may be comparable with the 3rd order contribution because the rate of increase of the 2nd order terms is greater than that of the 3rd order terms. Clearly, the contribution to i.p.s from 2nd order non-linearity could be important but could be eliminated by inserting suitable band-pass filters between each unit in the transmission path. It will, therefore, be neglected in the following estimate of the permissible level of intermodulation in one unit.

In the 'advanced' Field-Store Standards Converter there are 24 r.f. switches and up to 20 delay units in the transmission path. If −45 dB is the maximum permissible level of i.p.s relative to the fundamental luminance-carrier signal, and assuming identical non-linear laws in each unit, the level of i.p.s generated in each delay unit or switch must therefore not exceed −78 dB.

This estimate is approximate since in practice the non-linear characteristics in the delay units and switches would not be identical. Moreover, −45 dB is not an accurate figure for the luminance-interference protection ratio because

(a) the figure is based on interference with a monochrome signal from a single c.w. signal, whereas in practice the interference from two modulated signals would appear on the output colour picture.

(b) the interference level would vary in a systematic way due to the switching action of the conversion process.

Nevertheless, −78 dB seems a reasonable estimate

* This is the highest level of interference consistent with grade 1 in the EBU six-point impairment scale.

* This is only one way in which 2nd order non-linearity could produce the $f_1 - f_2 + f_3$ term. It could also be produced by $(f_1 - f_2)$ combining with f_3 and $(-f_2 + f_3)$ combining with f_1.

of the maximum permissible average level of 3rd order i.p.s generated in each delay unit and r.f. switch. In view of this stringent requirement it was decided that measurements were necessary to determine the degree of intermodulation actually present.

3. METHOD OF MEASUREMENT OF INTERMODULATION PRODUCTS FROM A SINGLE UNIT

Fig. 2 shows the experimental arrangement used for measuring the intermodulation products. Low-pass filters were included in the outputs of the oscillators to ensure a low level of 2nd harmonic content. Thus the generation of $2f_2 - f_3$ type i.p.s by 2nd order non-linearity was negligible compared to that generated directly from the fundamental frequencies by 3rd order non-linearity. The normal level of input signals to the unit under test was 0·25 V p-p for the f_1 signal (representing the luminance carrier) and 0·125 V p-p for the f_2 and f_3 signals (representing the colour-difference signals). The amplitude of the combined input signals was therefore 0·5 V p-p which was the intended working level for the delay units and r.f. switches in the 'advanced' Field-Store Standards Converter.

The levels of the i.p.s relative to those of the fundamental signals were measured with a receiver by direct comparison with a signal generator, the frequency and output level of which was adjusted to be the same as the unknown signal. Sharply-tuned 'notch' filters were inserted at the receiver input to prevent receiver intermodulation; two filters, one tuned to the higher level f_1 signal and the other to the f_2 signal, were found to be sufficient for this purpose.

Intermodulation in the oscillators due to coupling via the mixing network was such that the levels of the important i.p.s falling in, or near the band occupied by the proposed f.d.m. system, were about −90 dB relative to the f_1 fundamental signal. Thus, i.p.s generated in the unit under test could be measured to an accuracy of about ± 3 dB at −80 dB relative to the f_1 signal, improving to ± 1 dB at −70 dB relative to the f_1 signal.

4. RESULTS OF MEASUREMENTS ON TYPICAL UNITS

The purpose of the measurements was to determine the order of magnitude of the important i.p.s and to confirm the expected summation of i.p. level for units connected in cascade, rather than to investigate the precise mechanism by which the i.p.s were generated. Typical figures for the i.p.s of particular interest rather than detailed results of all the measurements made are therefore given.

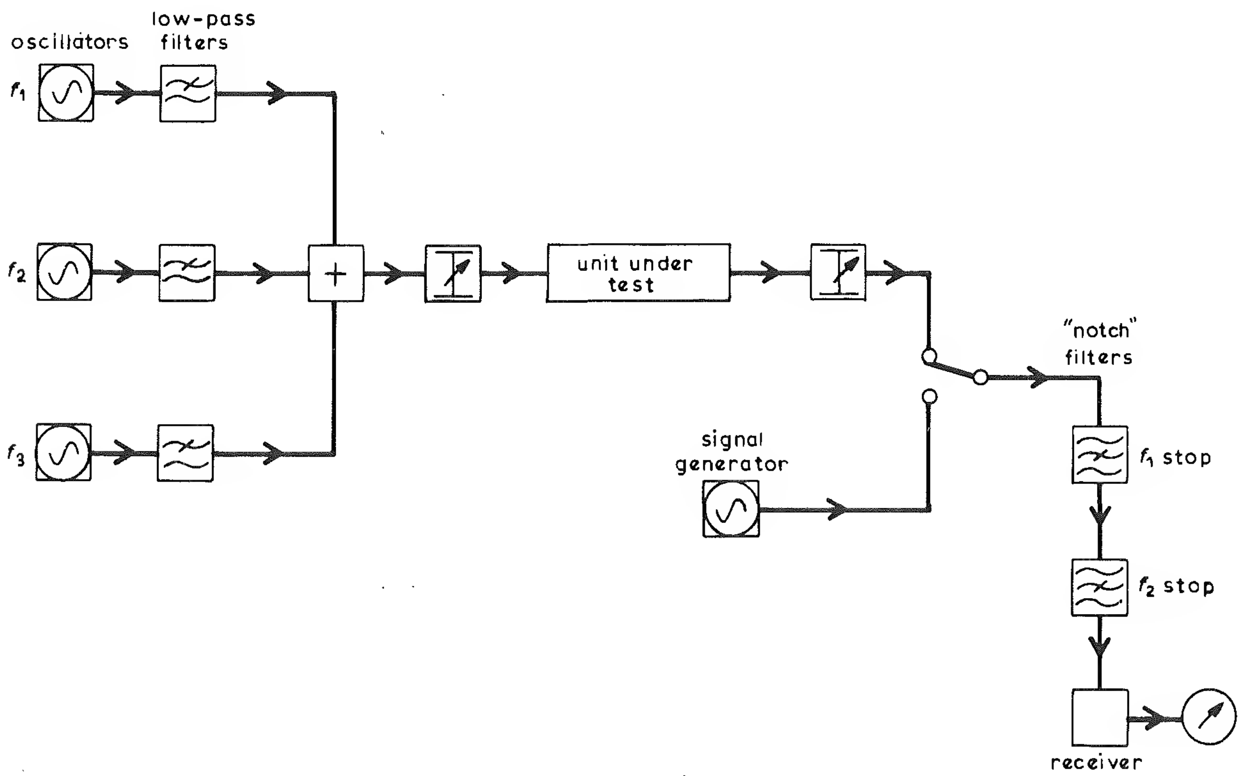

Fig. 2 - Experimental arrangement for measuring intermodulation products

Measurements were made on a number of r.f. switches both individually and with up to five switch-paths connected in cascade. Measurements were also made on the one delay-line unit which was available at the time. The results are summarized in Table 3, the figures given for the r.f. switch being the average of a large number of measurements.

TABLE 3

Frequency	Level relative to that of f_1, dB			
	R.F. switch	Delay unit		
f_1 f_2, f_3	0 −6	0 −6	fundamentals	
$2f_1$ $2f_2$, $2f_3$	−48 −50	−31 −39	harmonics	even-order terms
$f_1 + f_2$ $f_2 + f_3$	−43 −46	−30 −32	intermodulation products	
$2f_2 - f_3$ $f_1 - f_2 + f_3$	−77 −77	−51 −40	odd-order terms	

The measurements made on a chain of five switch-paths confirmed the expected addition of the 3rd order contributions from each unit. In fact the final levels tended to be somewhat higher than predicted indicating an in-phase contribution from the 2nd order mode of generation (band-pass filters were not inserted between each unit).

5. DISCUSSION OF RESULTS

The odd-order i.p. contributions from the r.f. switches virtually meet the target of −78 dB relative to the f_1 (luminance carrier) signal; band-pass filters would, however, probably be necessary to remove the effects of even-order non-linearity.

The odd-order i.p.s from the delay unit fall short of the target figure by a considerable amount (38 dB in the case of the three-frequency term). In a chain of 20 such delay units, the effects of even-order non-linearity would probably be comparable to odd-order non-linearity unless band-pass filters were inserted between each unit.

The predicted 12 dB difference in level between the two- and three-frequency odd-order terms is reasonably confirmed by the results on the delay unit but not by the measurements on the r.f. switches. This may be due to the fact that all the r.f. switches had been fitted with transistors specially selected for minimum non-linearity on the basis of a low level of the three-frequency i.p. ($f_1 - f_2 + f_3$) only.

The results show that the f.d.m. system as proposed is almost certainly ruled out by intermodulation effects, mainly in the amplifiers of the delay units. It seems unlikely that the non-linearity could be reduced to an acceptable figure.

5.1. Alternative Proposals

In view of the above results consideration was given to possible re-arrangements of the three carriers to minimize the interference from intermodulation products. Fig. 3 shows a disposition of the three carriers within a minimum bandwidth of about 11·5 MHz that might prove practicable, in which the principal 3rd order i.p.s fall in the space between the bands occupied by the f_1 (chrominance) and f_2 (luminance) signals. The indicated 'spread'

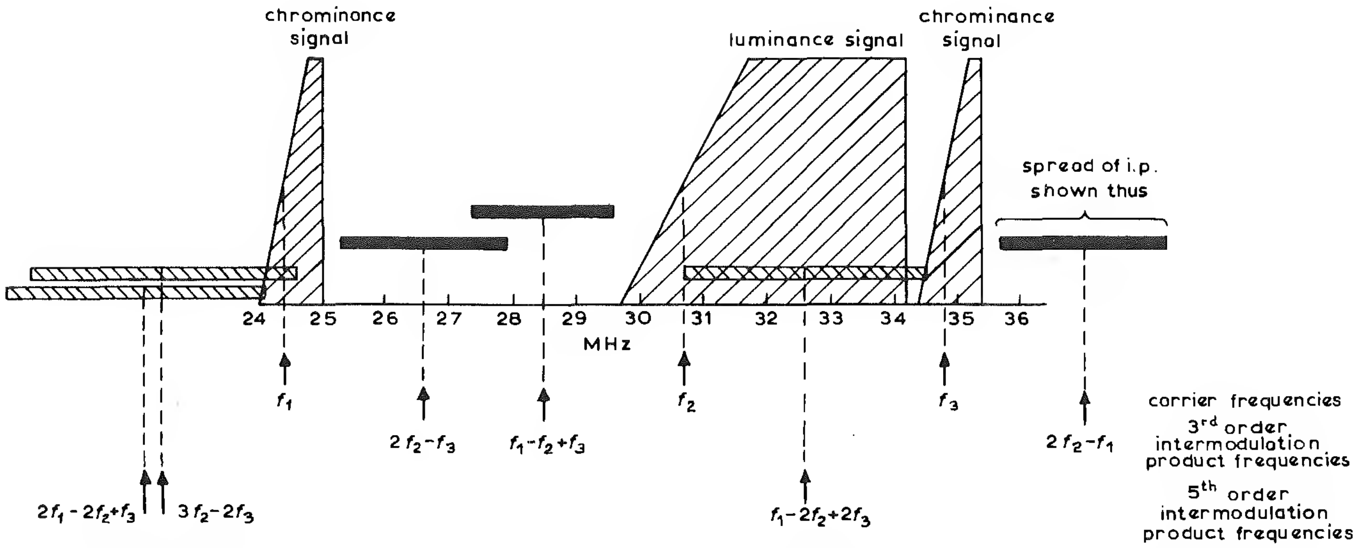

Fig. 3 - Approximate spectral components of possible f.d.m. system free from interference from intermodulation products

of each i.p. has been calculated on the basis of an f.m. deviation of ± 0·5 MHz for the luminance carrier and ± 0·3 MHz for the chrominance carriers. Theoretically, the spectrum of each i.p. would be much greater than shown in Fig. 3 due to the high-frequency sidebands of the component f.m. signals, and experiments would be necessary to determine whether, in practice, visible interference would result. Three 5th order i.p.s are shown which fall within the pass-bands of the wanted signals but measurements have indicated that 5th order products are unlikely to be sufficiently strong to cause visible interference.

6. CONCLUSIONS

A proposal to use a frequency-division-multiplex system, involving the use of two additional f.m. carriers to convey the colour information of a colour signal through the 'advanced' Field-Store Standards Converters has been examined. The results of measurements have confirmed that serious interference difficulties would arise from intermodulation products generated mainly in the delay units but with some contribution also from the r.f. switch units. The interfering products would be generated by both odd-order and even-order non-linearity but the effects of even-order non-linearity could be removed by inserting band-pass filters between each unit.

The interference results from the sum of the contributions from many units in the transmission path and it is unlikely that the linearity of each unit could be improved sufficiently to reduce intermodulation to an acceptable level. The problem could be minimized by increasing the separation of the carriers but a total bandwidth of about 11·5 MHz would be required and at present it would be both difficult and expensive to obtain delay lines of this bandwidth. Even if wider bandwidth delay lines become available, further work would be necessary to determine whether or not interference from sidebands of the intermodulation products presents a problem.

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